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By

Wilhelm Wiederhold

Translated from
Zeitschrift des Deutschen Vereins von Gas-
und Wasserfachmänner, 90, 24, 634 - 641 (1949)

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ON THE INFLUENCE OF DEPOSITS IN TUBES ON HYDRAULIC PRESSURE DROP

By Wilhelm Wiederhold,
Hildesheim

Zeitschrift des Deutschen Vereins von Gas- und Wasserfachmänner, 90, 24, 634--641 (1949)

Summary: In the first pressure section of the Ecker long-distance water pipeline, considerable decreases in the rate of flow occur in years of low operation which can be traced back to a special corrugation of the film of grease deposited in the system. The small depth of the deposit in relation to the pipe diameter and its technical flow behavior, different in nature from that of hitherto investigated roughnesses, make it probable that it is a matter of a new specific type of roughness.

The calculation of pressure drop of piping systems that was introduced by the DVGW (German Union of Gas and Water Specialists) for standardization of method of calculation* originated from the wall roughness of cast iron, steel, asbestos cement, centrifugal cast or lean concrete pipes usually used. This wall roughness, which is conditioned by the pipe material, interior insulation and method of manufacture, and therefore also is to be designated as manufacturing roughness, can be changed in hydraulic piping by deposits

*Cf. this journal, 90, 499--502, 1949.

from the water passed through and by processes of corrosion between the water and pipe material. While corrosion especially causes the formation of spots of rust which by increased wall roughness make themselves more or less perceptible in a reduction of capacity, deposits can occur in a form technically harmless to the flow but also can lead to very decisive reductions of capacity. In the latter case a very thin coating of the pipe with a specific roughness formation is sufficient to affect very strongly the flow conditions in the boundary layer in the direct vicinity of the wall. But as we know from recent research on flow, this boundary layer is decisive for the structure of the velocity distribution and hence for the capacity of the piping. The theoretical knowledge of flow in rough pipes comes from the classical investigations of Nikuradse [1]. The perfect sand roughness used by him has no direct analogy in practice, since even a large accumulation of rust spots permits no direct comparison with it, but subsequent works [2, 3] also have extensively revealed the influences of the depth of the roughness. The sand roughness of Nikuradse represents in this connection a simplified roughness, or a certain extreme of depth of the roughness. One must get the impression, from previous publications on investigations of a laboratory type [4], that there exists a roughness of a special type to which one, for the time being with certain reservations, can apply the concept, introduced by Hopf, of wall ripple [5]. Such an extreme of wall ripple as the perfect sand roughness of Nikuradse has not been known up to now. The concept of wall ripple, under the impression of the theoretical results of the investigations of Nikuradse, has gone somewhat into the background. But on the basis of the peculiar roughness conditions first noted in practice and measured at the Ecker Works it appears at least necessary to discuss these roughnesses not merely from the exclusive point of view of perfect sand roughness.

In addition to the known influences of rust spot roughness and the particular roughness of deposits to be dealt with in more detail here, the so-called incrustations also occurring in water supply systems remain unconsidered. They are due to formations of rust nodules and lime rust to a great extent, of lime sinterings and iron and manganese precipitates with their specific growths of bacteria, and lead not only to completely irregular changes in the wall roughness but also to decreases in its cross section, which can lead to complete incrustation of the pipe. To strive for a theory

for the calculation of the changes in capacity connected with this would be out of place. As soon as a change in the interior of the pipe exceeds a specific change in the wall roughness, and thus leads to irregular growths and decreases in cross section, it is a matter of a process with such non-uniform technical conditions of flow that any calculation becomes illusory. Here one can obtain a scale for the progression of the reduction in cross section by repeated measurement of the capacity or pressure drop and comparison with the measured or calculable original capacity [6].

The discussion of the peculiar roughness phenomena noted at the Ecker system* should be preceded by brief comments on the general theory of flow in pipe lines.

Calculation of the Technical Flow of Hydraulic Pressurized Pipelines

A discussion of this question on the basis of the theory of flow requires a presentation of the test data in the usual form of a curve of the function $\lambda = f(Re)$. Here, λ is the coefficient of friction as obtained from the general fundamental formula for the pressure drop

$$\frac{dp}{dx} = \lambda \frac{\bar{v}^2 \cdot \varrho}{2 \cdot d}$$

where $\frac{dp}{dx} = J$ is the energy drop. From this it is determined that

$$\lambda = \frac{\Delta p \cdot d}{\Delta x \cdot \bar{v}^2 \cdot \varrho/2}$$

where Δ p is the pressure drop in the length of pipe under consideration, kg/m^2;
Δ x is the length of pipe under consideration, m;
$\bar{v}$ is the average velocity, m/sec;
d is the pipe diameter, m;
ϱ is the density of the water, $(kg)(sec)^2/m^4 = \gamma/g =$ = specific gravity/acceleration due to gravity = = 102.

*Cf. this journal, 88, 161--166, 1947.

Table 1. Composition of the Various Deposits in Pipes

Rohrleitung (1)	NW (2)	MnO_2	Fe_2O_3	Al_2O_3	CaO	Unlöslich (3)	Glühverlust *) (4)	Wasser (5)	Rauhigkeit (6)
7 Eckerfernleitung	500	19,2	3,1	52.8	9,9	0,7	—	Reinwasser (11)	Riffelbelag (12)
8 Nebenleitung Oker	200	17,1	6,0	34,4	9,6	31,1	—	"	"
9 Sösefernleitung	800/000	8,6 (MnO)	4,4	10,1	43,7	2,8	27,4	"	Glatter Belag (13)
10 Turbinenleitung Söse	1200	43,6 (MnO)	9,9	7,0	2,2	17,5	20,7	Rohwasser (14)	Riffelbelag (12)

*The contents of H_2O, organic substances and CO_2 are contained in the loss upon ignition.

1 -- Pipeline; 2 -- Nominal diameter; 3 -- Insoluble; 4 -- Loss upon ignition; 5 -- Water; 6 -- Roughness; 7 -- Ecker pipeline; 8 -- Oker by-pass; 9 -- Sose pipeline; 10 -- Sose turbine pipeline; 11 -- Pure water; 12 -- Corrugated deposit; 13 -- Smooth deposit; 14 -- Natural water.

Table 2. Change of Throughput in the Ecker Pipeline

	Druckabschnitt (1)	NW (2)	Werte 1943 (3) $Q_{l/s}$	Werte 1943 (3) $v_{m/s}$	Werte 1946 (4) $Q'_{l/s}$	Werte 1946 (4) $v'_{m/s}$	Änderung in v.H. (5)	Gefälle m/km (6)
I	WW Ecker - HB Wolfstein	500	600	3,06	343	1,75	57,1	12,5
II	HB Wolfstein - HB Lewerberg	500	560	2,86	320	1,63	57,1	11,0
	(7) Nebenleitung Oker	200	52	1,65	32	1,02	61,5	12,7

1 -- Pressure section; 2 -- Nominal diameter; 3 -- 1943 value; 4 -- 1946 value; 5 -- Change in %; 6 -- Drop, m/km; 7 -- Oker by-pass.

The need to introduce the Reynolds number in consideration of theoretical flow arises from the law of similarity which applies here, inasmuch as comparison of the experimental results on geometrically similar pipelines only becomes possible through consideration of that law. Quite generally one considers two flow processes similar if geometrically similar shapes of the channels are present (open or closed) and if homologous values of the same type (forces, velocity, etc.) stand in the same relation to one another, whereby this ratio can be distinguished according to the type of values. Inertia, gravity and frictional force come into question in this. If the ratio of frictional force to inertia is predominant, the Reynolds law of similarity is valid, and if that of gravity to inertia, Froude's law.

In a problem of purely frictional forces, as is the basis of the question of pressure drop in pipes, the Reynolds law of similarity applies. According to it, two or more flows are similar, and therefore comparable, if the ratio of the frictional force to inertia at corresponding points of the flows in question always is the same. This condition is fulfilled if both flows exhibit the same Re number: $Re = \frac{\bar{v} \cdot d}{\nu}$.

Here $\bar{v}$ and d are characteristic values, the first of which can be equated with the mean rate of flow and the latter to the diameter of the pressurized piping. In the coefficient $\nu =$ = the kinematic viscosity, the hydraulic nature of the fluid is expressed. By substitution of the corresponding kinematic viscosities all the flow processes with various fluids, for example, gas, air, water, oil, etc., become mutually comparable. Modern investigations of flow make extensive use of these conditions of similarity in investigation of models on flow machines through the use of air as the test medium instead of steam or water, or conversely, water instead of air or gases [7].

The hydraulic calculation of pressurized pipings is based on the conditions $\lambda = f(Re)$ from Figure 1. The latter are derived from measurements of pressure drop of the Sose pipeline* which permit no changes at all to be perceived after 15 years of service, and thereby can give the prerequisites for a practical basis of calculations embracing all the normal

*Cf. this journal, 81, 382--389, 1938.

influences, especially such ordinary deposits [8]. By ordinary deposits here is understood a film of lubricant whose surface roughness is not greater or not much greater than the manufacturing roughness of the pipe. This pipe deposit, which has reached a thickness of 2 to 3 mm in the Sose piping, has a smooth, somewhat velvety surface; its chemical composition is given in Table 1.

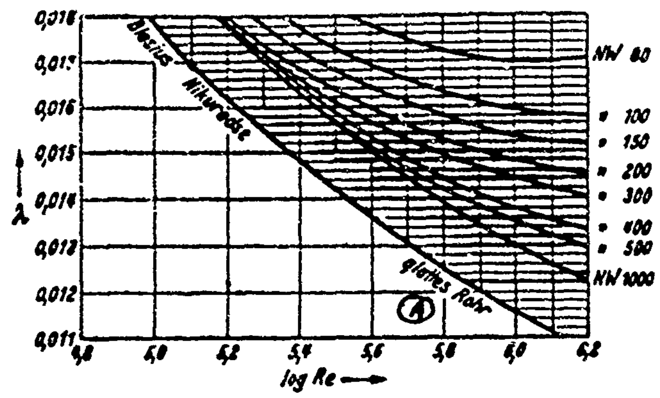

Fig. 1. The coefficient of resistance λ as a function of the Reynolds number Re for hydraulic pressurized pipelines.

NW = Nominal diameter. A = Smooth pipe.

It is evident from Figure 1 that the coefficient of resistance λ generally becomes smaller with rising values of the Re number. With completely smooth pipes, for example, polished brass pipe, this course of the curve λ_{smooth} is independent also of the pipe diameter. In pipes ordinarily used, on the other hand, a double influence of the nature of the wall is perceptible. On the one hand is the wall ripple, which indicates that the value of λ lies about 10% above the corresponding value of λ_{smooth}, and the curve of the coinciding values of λ thus runs parallel to λ_{smooth}. On the other hand is the wall roughness, which has the result that the values of λ of the individual pipe diameters in turn are removed from this leg of the common curve.

Additional Pressure Drop in the Ecker Pipeline

The hydraulic calculation of the Ecker pipeline gave excellent agreement with the measurements made before it was put into service in 1943. As early as 1945 severe decreases in capacity were discovered, which in 1946 rose to the values presented in Table 2.

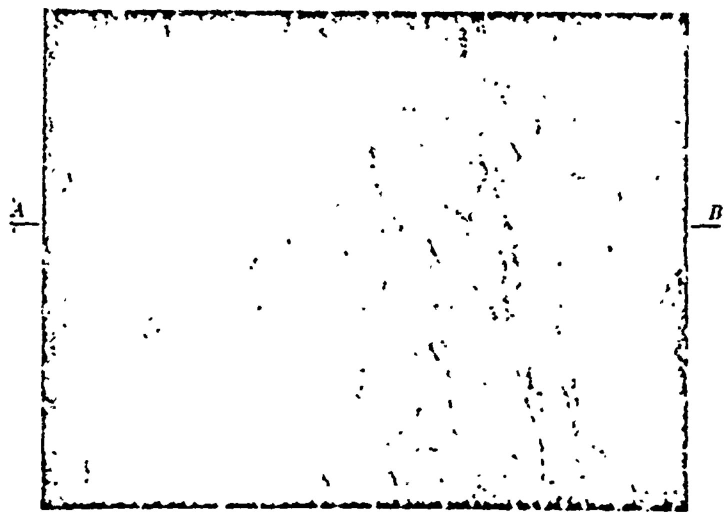

Fig. 2. Ripple-formation in the coating in the pipe of the Ecker pipeline, 500 mm in diameter (natural size; illumination from the right, direction of flow from left to right).

At first no indication of the reasons for these decreases in capacity could be found. On the basis of the available daily pressure and quantity measurements in the supplying of the individual high-level tanks it could be established that the decline in capacity of this gravity pipeline had increased steadily with the period of service. Then, in Pressure Section II in particular, repeated measurements were made at different rates of flow at numerous points on the pipeline with a precision manometer and plotted in the longitudinal section; they always gave a completely steady pressure drop over the entire 18-kilometer section of pipeline. It could therefore only be a matter of a uniformly distributed additional pipe roughness. Repeated inspections of the inside of the pipe carried out at various points with branch pieces appeared at first not to confirm this assumption. From the 1943 and 1946 values of the head a degree of roughness was calculated of $r/k = 40$ ($Re = 5 \times 10^5$) to $r/k = 17$ ($Re = 1.38 \times 10^5$) as equivalent to the sand roughness according to Nikuradse, and with it a uniform elevation of roughness of 6.2--14.6 mm would be assumed. But only a uniformly distributed coating of the inside of the pipe appeared at all points, consisting of a thin layer of lubricant, about 0.5 mm high in the middle, which could readily be wiped off

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* Editor's Note: The photograph of this Figure and those of the subsequent Figures in this article were made from Xeroxed copies; better copies were not available.

with the finger to expose the completely intact, glass-smooth bituminous insulation underneath. The opening of the entire pipe cross section of the pipeline with NW (nominal diameter) 500 by driving in an expander showed a certain roughness in the form of a thin film of lubricant occurred in the form of a characteristic rippling.

Fig. 3. Ripple-formation in sand dunes through wind flow.

This rippling (Figure 2) runs in a disordered fashion in individual parts but in general quite uniformly and almost perpendicular to the direction of flow, hence in the radial circumference of the pipe. Between the individual ripple elevations is the totally uncovered, smooth bituminous surface of the inside insulation; the similarity to the well-known formation of ripple formations in sand caused by flows of wind and water is obvious (Figure 3). The significant pressure drop was hardly explicable, however, at so small a thickness of the coating, the ridge height of which was estimated to be 1 mm at its highest. Therefore it had to be a matter of a special type of roughness which cannot be compared directly with perfect sand roughness. The assumption that there it is a matter of some sort of flow resonance in the boundary layer was natural, but no reference or indication

could be found in the available literature. In order to get to the root of the matter and to be able to undertake the required measurements and evaluation from the point of view of modern flow theory, the Engineering Office for Applied Flow Technique (Ingenieurbüro für angewandte Strömungstechnik), Professor Seiferth and Dr.-Eng. Krüger, Göttingen, were brought in for consultation in an advisory capacity.

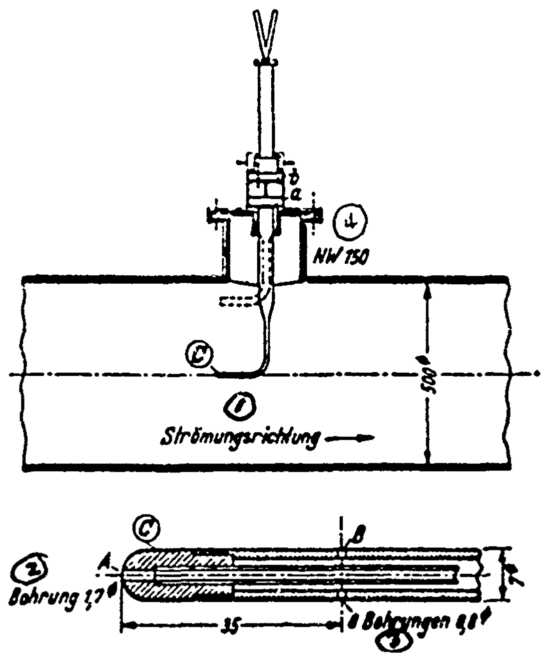

Fig. 4. Prandtl pressure tube measuring arrangement.

1 -- Direction of flow; 2 -- 1.7 mm bore; 3 -- 0.8 mm bores; 4 -- NW = Nominal diameter.

Measurement of the Additional Pressure Drop

At first the influence of so small a coating (in causing a reduction in flow of about 60%), in spite of the observed ripple roughness from this aspect, was considered improbable. It was therefore agreed to measure a straight 178.1-meter stretch of pipe, without installations reducing the cross section, very precisely hydraulically. In it the measured pressure drop was of the order of magnitude of the measured pressure drop in the entire Pressure Section II, and so the additional drop probably could be attributed to the ripple-formation of the coating. Cleaning of the stretch and

a second measurement of the pressure drop had to provide a conclusive confirmation and these measurements had to agree approximately with the original values of the calculation and measurement.

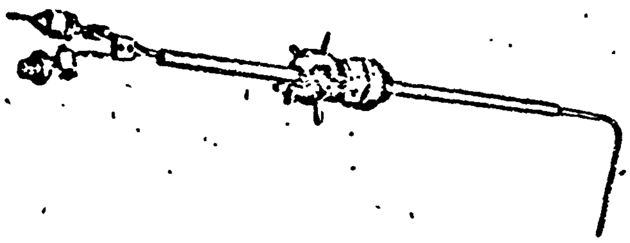

Fig. 5. Prandtl pressure tube with stuffing box and clamping device.

The measurements were undertaken with Prandtl pressure tubes in the arrangement shown in Figure 4. The pressure tubes were introduced on two vertical 150 mm branch pieces at the ends of the measured stretch in the 500 mm piping. Between the stuffing boxes and the clamping device on the graduated flask (Figure 5), the pressure pipes could be moved over half the pipe diameter and fixed against the internal pressure of the pipe (up to 27 atmospheres gage) at every point. The special arrangement of the measuring instrument was supplied by the Otto Otto firm, Fine Machinery Workshops, Hildesheim, according to specifications.

Next the pressure drop was measured in the measured stretch, the total pressure p_{tot} of the two Prandtl tubes in the axis of the pipe being connected together to a differential manometer filled with acetylene tetrabromide ($\gamma = 2.94$). For this purpose the two measuring points were connected to the differential manometer by lead conduit 13 x 18 mm in size. The pressure drop was determined at the different rates of flow. The flow was adjusted by means of the inlet slide valve of the high-level tank behind the measured stretch, and the measurement was made with a Venturi meter at that point. As a further series of measurements the profile of the velocities

was taken at maximum throughputs. For this purpose the dynamic pressure was measured with a differential manometer as the pressure difference occurring between points of measurement A and B (Fig. 4). Here the total pressure occurring at point A corresponds to $p_{tot} = p + \frac{\gamma}{2g} \cdot v^2$, the static pressure measured at B is p, the difference between the two, the dynamic pressure or head Δp = the total pressure p_{tot} - the static pressure $p = \frac{\gamma}{2g}v^2$. Hence $v = \sqrt{\frac{2g}{\gamma}\Delta p} = 4{,}4 \cdot \sqrt{\Delta p}$, that is, the magnitude of the velocity is given directly from measurement of the pressure difference A - B. The velocity profile distributed over the pipe cross section is symmetrical with respect to the axis of the pipe, and so determination of the profile over the pipe radius is sufficient. These velocities were measured by means of a movable test probe over the pipe radius at a distance of 2 cm, and in the vicinity of the wall at a still shorter distance; definite conclusions about the roughness of the inner wall of the pipe can be shown at once from the velocity distribution constructed from this, and integration of the velocity profile gives control of the measured rate of flow at the Venturi numbers of the high-level tank. It was established in the measurements that at a certain exceeding of the pipe axis corresponding to a free distance between the clamps of the probe on the measuring flange of about 500 mm, stronger vibrations of the Prandtl tube set in, in spite of apparently stable installation. They were ascribed to eddy formations of the flow on the probe. The measured values were taken five times consecutively at two-minute intervals. The points obtained from the average values were plotted on the spot in order to repeat the measurement at once when there was a deviation.

These measurements, which required a few hours, were replaced by photography of the wall roughness (Figure 2). For this purpose, two branch pieces 150 mm in diameter were needed at measuring point II in a sliding shaft. The wall opposite was photographed with a Leica camera through the horizontal piece, and strong illumination from the side was arranged with an electric bulb through a vertical 150 mm piece located downstream in the flow. The picture taken is a cut out segment in natural size that permits this type of ripple-formation to be readily distinguished.

Results of the Investigation

Direct measurement of the crest height of individual ripples and the average distance between them is not possible due to the structure of the deposits. On a cutout portion of the bituminous insulation, taken with the probe, with the deposit on it, finely divided particles crumbled off later when it was carefully dried. Likewise, making a plaster cast of it seemed impossible. Therefore a photogrammetric plotting of Figure 2 was made. As the smooth places lying between the individual crests represent the level of the bituminous surface, the height of the roughness can be obtained from the lengths of the shadows of the ripples at a known position of the light source. Figure 6 shows these measurements in the section A - B of Figure 2. The average distance of individual crests is about 5 mm. The heights are at a ratio of 10 : 1 and give an average elevation of the roughness of about 0.7 mm. In the face of these slight increases in the thickness of the deposit, which represent about 0.3% of the pipe radius, their influence on the size of the pressure drop is simply astonishing.

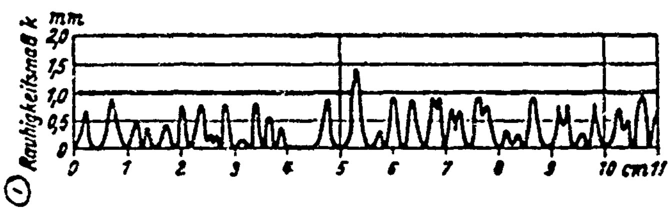

Fig. 6. Roughness profile in section A - B of figure 2.

1 -- Measure of roughness k.

In Figure 7 the experimental results are presented for the 500 mm pipe in question of the Ecker pipeline. The pressure drops of the original capacity (curve a), based on calculations, were confirmed by measurements before definite start-up of the line. Then registration of the λ values of the test measurements (curve b) gives the plotted course. It clearly shows the influence of both the wall roughness and of waviness of the ripple-formation. The latter is expressed in a displacement parallel to λ_{smooth}, the former in general elevation of the λ value. The ratio of the measured λ values to the original is about 2.85, which means almost a threefold increase in the pressure drop, corresponding to a reduction in flow of

$$Q' = \frac{Q}{2{,}85^{0.55}} = \frac{0{,}560}{1{,}75} = 0{,}320 \text{ m}^3/\text{sec},$$

if one takes as a basis the approximate function

$$Q_{\text{m}^3/\text{sec}} = J^{0.55}_{\text{m/km}} \cdot d^{2.70}_{\text{m}}$$

The throughput of the Ecker 500 mm main pipeline was thereby reduced to the capacity of a line 400 mm in diameter.

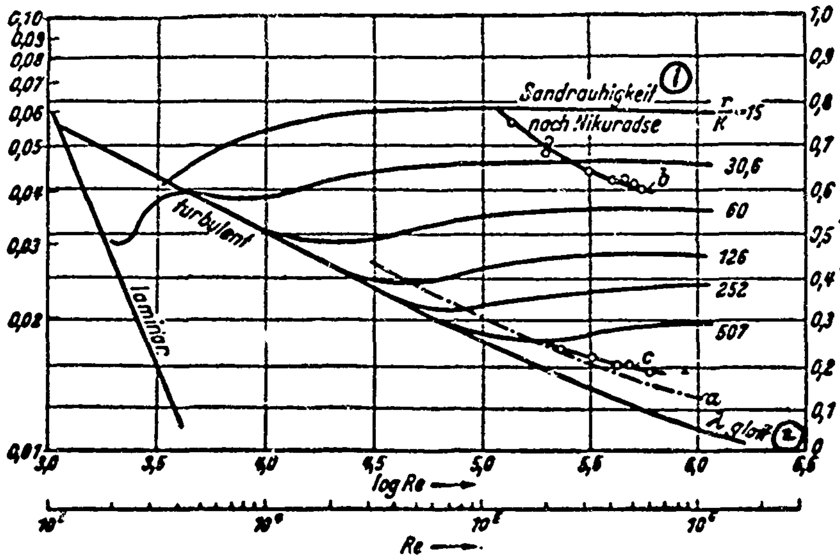

Fig. 7. The dependence of $\lambda = f(Re)$ for sand roughnesses and roughness ratios of the Ecker long-distance water pipeline. The resistance value a is that of the original capacity, b that of the ripple-formation and c that after cleaning of the pipe.
1 -- Sand roughness according to Nikuradse;
2 -- λ_{smooth}.

Likewise interesting and informative is the plotting of the measured velocity profile. Figure 8 shows its course, where the dimensionless representation is chosen in which the measured velocity v is introduced for the average velocity $\bar{v}$ and the wall distance y in relation to the pipe radius R. For comparison, the profiles of a smooth and of a completely rough pipe with the roughness ratio r/k = 15 according to Nikuradse are shown. The tapering of the Ecker profile allows the influence of the character of the wall at low y/r

values to appear clearly. The relatively high complete sand roughness of the profile measured by Nikuradse still does not itself come up to the estimate and plainly shows the great influence of ripple-formation in spite of its insignificant all-over dimensions. Integration of the velocity profile gives a quantity of 312 liters/second and a satisfactory agreement with the Venturi meter measurement of 305 liters/second.

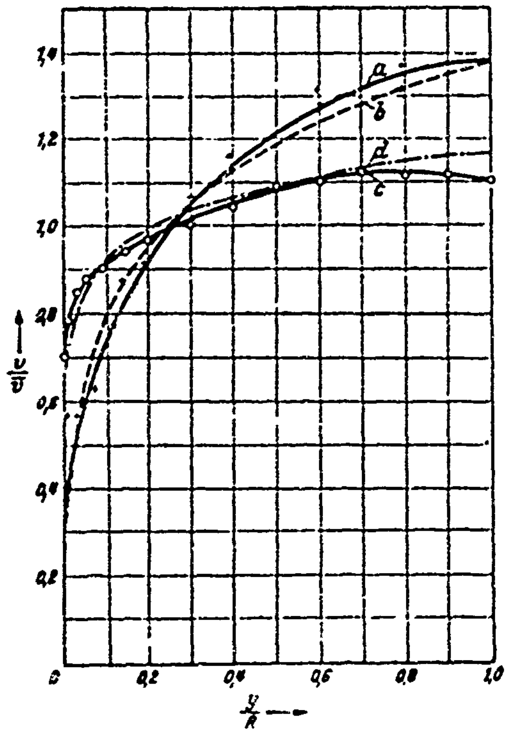

Fig. 8. Velocity distribution $v/\bar{v} = f(y/R)$.
a -- Measurement of the pipe 500 mm in diameter with ripple-roughness;
b -- Profile according to Nikuradse for sand roughness r/k = 15;
c -- Measurement on the cleaned 500 mm pipe;
d -- Profile according to von Karman for smooth pipe.

Evaluation of the Experimental Results

The resistance values determined in the test stretch agreed with those measured in the entire pressurized sector. From this it could be assumed that the additional pressure drop is, with high probability, to be attributed to the observed ripple-formation of the pipe deposit. The unusually

high final pressure drop, and also the striking decline of the λ values with the Ryenolds number, which especially permits no direct comparison with the complete roughness measured by Nikuradse, show that it is a matter here of a special sort of flow process. The Engineering Office of Professor Seiferth and Dr-Eng Krüger, meanwhile, with the help of a work by H. Schlichting, was able to make a first clarification of this question, which should be given again here essentially in their version.

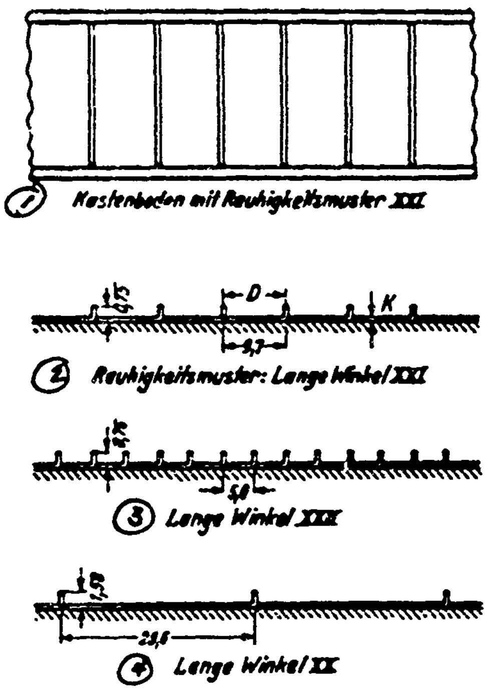

Fig. 9. Roughness pattern of "long angles" according to H. Schlichting.

1 -- Housing with roughness pattern XXI; 2 -- Roughness pattern: long angle XXI; 3 -- Long angle XXII; 4 -- Long angle XX.

Nikuradse's work on so-called completely rough pipes proceeded from the well determined roughness of pipe wall roughness uniformly cemented with sand of uniform size. The roughness factor is represented in that case by the r/k ratio, in which r is the pipe radius and k the size of an average grain of sand. The function $\lambda = f(Re)$ for completely rough pipe and various roughness factors is evident from Figure 7. Roughnesses with a completely different structure were

investigated by Schlichting. In them, not only was the pattern of the roughness varied, but also its thickness. For this purpose, spheres, cones, cups, an open box channel and "short" and "long" angles, with varied dimensions and distances, were used as a basis (Fig. 9). These idealized patterns of roughness, especially the long angles, essentially come closer to that of the Ecker pipeline than to the sand roughness according to Nikuradse. Patterns XX to XXII especially are of comparable order of magnitude and arrangement. If the results obtained by Schlichting are converted to the ratios of the Ecker pipeline, the course shown in Figure 10 is obtained. Here it was not the direct function $\lambda = f(Re)$ that was established, but the dimensionless wall shearing stress $\tau r/\rho \bar{v}^2$ formed a value which also characterized the coefficient of friction in the pipe. The course of the curves of patterns XX and XXII shows that the latter are influenced by the Reynolds number only a little and thus a form of complete roughness is present. A systematic dependence on Re is to be found only for pattern XXI, where it decreases in a similar way to the λ values in the Ecker pipeline.

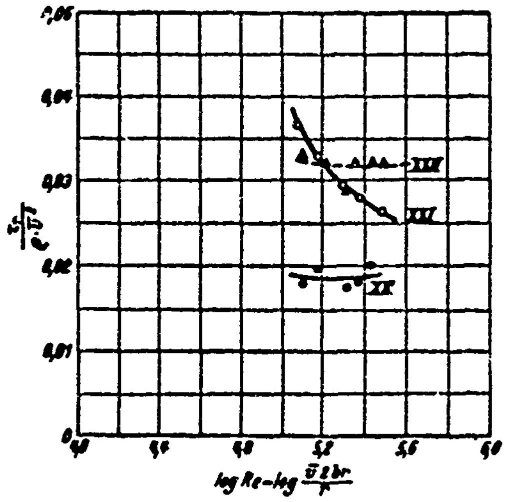

Fig. 10. Resistance as a function of the Reynolds number Re for the roughness pattern according to H. Schlichting.

This very valuable finding gives a first indication of where the further scientific pursuit of the problem can be applied. The anomaly established only with this roughness

pattern means that the condition of the squared resistance law is not satisfied here. The assumption that other technical flow conditions are present in ripple roughness as in complete sand roughness therefore is probable. These assumptions have been reinforced by newer investigations [4]. The unusually high increase in resistance in spite of the small height and thickness of the roughness is explicable a priori only if a certain resonance effect of vortices in the boundary layer is assumed, for the formation of which the ratio of the roughness height to the distance between the individual roughness elements is decisive. It is surprising, then, that the flow from the deposit constructs this critical geometric ratio itself and thereby apparently tends toward a maximum roughness.

Results of Cleaning the Pipe

As previously mentioned, the final proof of the investigation of the problem by measurement should be produced by cleaning the pipe. True, according to the earlier determination and the conclusion to be drawn from it the exclusive influence of the ripple formation can hardly be doubted any more, but the last percentage of probability was to be obtained only by removal of the wall roughness and re-measurement of the test section.

This proof could be produced. After cleaning of the test section with suitable equipment, a description of which will be given below, the same measurements were made again in the same sequence. The resistance values of the original line are approximately regained in so doing, as is evident from curve c of Figure 7. The velocity profile (Figure 8) curve d gave a course which closely agreed with the theoretically determined velocity distribution in a smooth pipe obtained by von Karman. No measurement of the velocity profile was obtained in the line in its original condition, and so a comparison can be made only with the theoretical curve. The measured velocity profile shows a slight indentation in the middle of the pipe, which is to be attributed either to measurement errors or to the fact that the measurement could be made only on the tube radius and the velocity distribution must not be absolutely axially symmetrical. In the measurement conditions of a pipeline in service, which are substantially more difficult than laboratory measurements, the measured values are to be characterized as very good and the deviations as of an order of magnitude which can hardly distort the overall picture.

At the conclusion of those measurements, cleaning of the rest of the pipeline was started. Since, because of limited reserve tanks, this can be done only on Sundays, up to now only the stretches in pressurized sections I and II have been cleaned. The improvement in capacity now obtained can be readily determined mathematically and is quite in agreement with the subsequently observed flow values. Hence it can be concluded that the cleaning is almost perfect, and this also is confirmed by the various inspections of the cleaned pipeline which again allows a completely smooth bituminous surface to be perceived.

Cleaning the Pipeline

It seemed necessary to develop cleaning equipment ourselves, as the known equipment such as tube cleaners and scrapers are not adapted in their method of operation to the task at hand. Damage to the insulation of the steel pipe had to be especially avoided, and the insertion and removal of the equipment had to conform to the existing conditions of the design of the pipeline.

The cleaning had to be done at times between two main gate valves; these parts, made in the form of ring sleeve valves, are located at a distance of 4 to 5 kilometers in accessible side shafts. In front of the slides are expanders with a 500 mm free insertion length, so that the insertion of cleaning equipment in that place is relatively easy. But removing it at the other end of the section presents great difficulties on account of the absence of accommodations for dismantling. This can be circumvented if equipment working in both directions is available.

After the currency reform one could think of approaching the question of our own development of the necessary equipment. First, a leather ball with an inflatable rubber bladder was made for cleaning a branch of the main pipeline 200 mm in diameter which serves to supply Oker Chemical Industries, the city of Goslar and the Goslar Railroad. A deposit had also formed in like manner in that line and its throughput dropped from an original 52 liters/second to 32 liters/second. Pretesting of the round leather ball permitted us to find out that in the branch piece the ball lodged in the branch section of the pipeline and could be driven further only with a large quantity of water. The same was to be expected in the globular mortised socket with its

greatly widened inside diameter. The final design consisted then of an inflatable leather ball in the shape of a shell with a leather cuff attached to it, which was to provide additional sealing of the pipe wall. The ball withstood an internal pressure of up to 3.5 atmospheres gage but only about 2.5 m of upstream face, in order to bring sufficient contact pressure to bear on the pipe wall. The driving pressure was between 1.0 and 1.5 m of upstream face.

The branch line 4.5 km long was cleaned with this ball. After insertion in the empty line and inflation to the prescribed pressure the ball was sent, at 0.5 m/sec corresponding to a water quantity of about 15 liters/second, through the line with several branch pieces 80 mm in diameter, a grooved slide and several pipe elbows, and came out at the end through a detachable grooved slide. After the line was flushed out and put in service, measurement gave the original throughput of 52 liters/second. On the basis of this throughput, as well as the amount of slime removed, complete cleaning was to be assumed.

It was not necessary to construct cleaning equipment on the same principle for the main line 500 mm in diameter, since operation in both directions had to be required there. Detailed calculation showed further that with the necessary large surface of the leather wrapper the internal pressure had to be kept very low in order to prevent bursting the seams. In that way the driving pressure and internal pressure decline in the same order of magnitude, and at larger driving pressures the ball collapses and the amount of water leakage becomes too great, in rising pipelines under certain conditions so great that the ball bursts. It was necessary to go to a new method.

The final solution was so simple that later the question was why one did not arrive at it at once. It consists in a cylindrical plunger made of sponge rubber fitted to the pipe diameter, the contact pressure and feed pressure of which can be controlled within required limits under axial stress (Figure 11). In this way the equipment is placed in the pipeline without difficulty and also can slip through the sectionally welded bends, if its overall length were reduced. In order to eliminate possible tilting it was divided in sections, flexibly connected together. In its practical test it has given satisfactory results up to now. The equipment was put in the empty pipeline in the described manner and driven

without a cable through the pipeline at a small overpressure of about 1 meter of upstream face at an average forward thrust of 0.5 m/sec. The leakage losses were very small, as in case of need one can destroy the device with higher pressure and the rubber can be washed out during the next low-point evacuation. The pressure drop, which in any event cannot be eliminated from the line, is without substantial importance for the throughput.

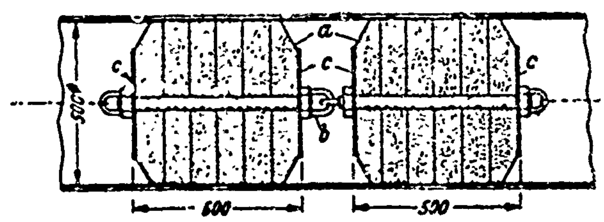

Fig. 11. Pipe cleaning apparatus for the main pipeline 500 mm in diameter.

New Knowledge

The findings obtained are in many respects conclusive and give certain direct indications for practical use.

From the viewpoint of the flow it is technically important that even thin films of lubricant can lead to surprising reductions of throughput in hydraulic pipelines, as soon as ripple formation occurs. In the presence of substantial declines in throughput or addition pressure drop during service, as long as rule spot formation or decided reductions in diameter are not present, greater attention should be given to the formation of a deposit in the pipe. That ripple formation could also occur in the presence of very varied chemical compositions of the pipe deposit could be established more than once in the meantime (Table 1). Thus a well-defined rippling manifested itself in the deposit of a turbine line 1200 mm in diameter at the Sose Dam power plant that consisted essentially of organic substances and manganese deposits from the natural water passed through the dam. In another case, through subsequent reaction of lime precipitates in the pipe behind the reactor a compact soft deposit formed, which gave rise to severe calc-sinters from crystalline lime on the pipe wall. Along with the deposit with a relatively smooth surface, ripple formations prevailed in a great variety of stages and structures (Fig. 12). It appeared that the precipitates

with a large lime content adhere more firmly to their underlayer, especially in asphalted cast-iron pipes and fittings.

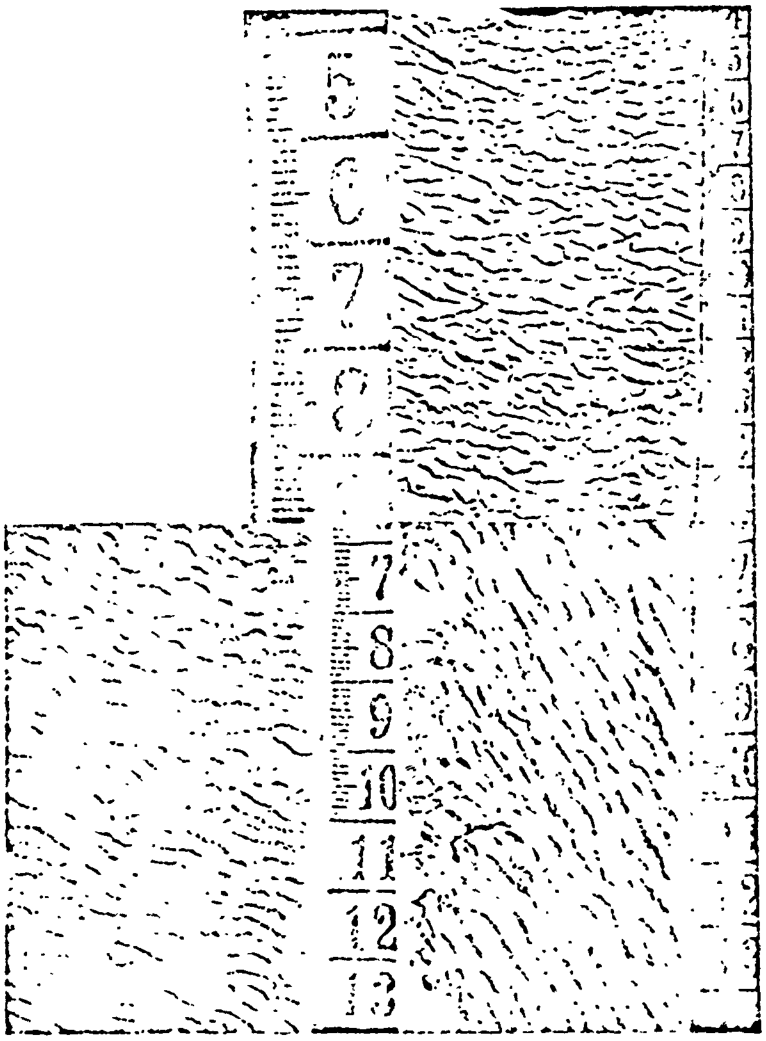

Fig. 12. Calc-sinters with smooth and rippled surfaces.

The reductions in throughput because of deposits also give indications of definite shortcomings in the water treatment. The deposit in the Ecker line contains a substantial portion of aluminum hydroxide along with organic substances; in the absence of a selection of water-treatment chemicals during the war and post-war years it could not be avoided that, with the use of aluminum sulfate as a precipitating agent, aluminum hydroxide occurred in very finely divided form in purified water. Since the entry of aluminum into purified

water was prevented by the changeover to sodium aluminate treatment, increase in the pressure drop has no longer been observed [9]. Hence it is probable that the ripple formation in this case was caused predominantly by the presence of finely divided aluminum hydroxide. Additional observed cases show that the chemical nature of the deposit cannot be called the exclusive factor for the possibility of ripple formation. Likewise, the velocity conditions alone cannot be cited as an explanation; they seem to have an influence only on the structure of the roughness. One would rather suspect that both conditions, the chemical nature and the flow conditions, but probably also the particle sizes of the sediments and their chemical nature, are determining factors in this.

For the practical worker it is of value that the hydraulic measurements of the pressure drop, the velocity profile and the throughput can be obtained with sufficient accuracy by means of the presented method of measurement, with little expenditure for equipment and labor, in pipelines in service. New indications can result from this for determination of a piping system's losses in larger lines. Furthermore, with the pipe-cleaning equipment that has been developed there exists the possibility of removing such pipe deposits without special difficulty and economically. It also is likely that firmly adhering deposits can be cleaned by the insertion of suitable wire brushes or proper equipment without cables. For the pipeline designer the question arises whether it is not advisable to provide for meter connections as well as enlarged pieces for the introduction of cleaning equipment generally in large-diameter lines.

There can be sufficient practical interest in purely scientific investigation of the questions raised, both with respect to technical flow and morphological questions about the ripple formation and on determining which deposits are prone to ripple formation. The cases of ripple formation which it already has been possible to observe in the short time since recognition of their importance permit one to conclude that they are more widespread than could be suspected at first. The economic consequences of these roughness formations could reach surprising amounts. Thus the example from the Ecker long-distance pipeline reduces a free gravity line of 13 million to scarcely 10 million m^3/year. In larger pump-pressurized pipelines the unnecessary operation of the pump to overcome ripple roughness can have a considerable negative effect on the books over long years of service. What

importance and scope ripple roughness has in the rest of technology in addition to pressurized pipelines still has to be demonstrated.

For water-supply engineering, important indications also result both for the inspection and maintenance of the piping system and for water treatment. It would be interesting and extremely valuable in more thoroughly understanding this new knowledge if observations of it were sent in to the DVGW, which will lead to their further evaluation.

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